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Throughput Analysis of IEEE 802.11 and IEEE 802.11e MAC

Pierre Ferré, Angela Doufexi, Andrew Nix and David Bull

University of Bristol, Centre for Communication Research

Woodland Road, Bristol, BS8 1UB, UK

Email: {Pierre.Ferre, A.Doufexi, Andy.Nix, Dave.Bull}@bristol.ac.uk

Abstract—This paper focuses on a throughput analysis of the IEEE 802.11 Medium Access Control (MAC). In the IEEE 802.11 standard, the main access scheme is called the Distributed Coordination Function (DCF) and is the basis for other access schemes, such as the Point Coordination Function (PCF) and the Enhanced DCF (EDCF) of the new IEEE 802.11e MAC. Since the IEEE 802.11 MAC does not support Quality of Service (QoS), the IEEE is currently working on the final draft of an enhanced version known as the IEEE 802.11e. In this enhanced standard, QoS and service differentiations are supported. The throughput and delay performance of the DCF/PCF of the IEEE 802.11 MAC are presented for different packet lengths and different numbers of users. Throughput performances are also detailed for the EDCF.

I. INTRODUCTION

The IEEE 802.11 MAC provides a shared access to the wireless channel and offers two operating modes. The first one is mandatory and is called the DCF. It defines a distributed access for an ad-hoc network. The second operating mode called the PCF and is optional. It defines a centralised access for an infrastructure network [1]. However, both modes are based on the same Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) access protocol. The DCF is used as a basis for the PCF. The DCF mode is also defined as the Contention Mode, whereas the PCF is known as the Contention Free Mode. If the optional PCF is used, it shall then alternate with the DCF in a super-frame. One of the main drawbacks of the IEEE 802.11 MAC is the lack of QoS support for real-time applications and for service differentiation. The new and enhanced IEEE 802.11e standard offers new features that support QoS and service differentiation. This is implemented in the EDCF. The physical layer (PHY) used in this paper is the IEEE 802.11a PHY at 5GHz. This is a Coded Orthogonal Frequency Division Multiplexing (COFDM) based physical layer. The physical layer provides 8 operating modes from BPSK 1/2 rate (mode 1) to 64 QAM 3/4 rate (mode 7) capable of providing data rates up to 54 Mbit/s [2] [3]. In section II, the mandatory DCF is detailed. The optional PCF mode is discussed in section III. In section IV, a study based on Markov chains highlights the impact of the number of users. Section V details the new enhanced IEEE802.11e leading to conclusions in section VI.

II. DISTRIBUTED COORDINATION FUNCTION

The DCF provides the basic asynchronous and contention-based shared access to the medium. It is a distributed scheme

for ad-hoc networks and is based on CSMA/CA. CSMA/CA is also known as ‘Listen before Talk’. Before a station starts a transmission, it shall sense the wireless medium to determine if another station is transmitting. If the medium is sensed as idle, the transmission may proceed. If the medium is as sensed busy, the station shall defer until the end of the current transmission [4]. DCF describes two techniques for transmission. The basic scheme is mandatory and is known as a two-way handshaking technique. It is characterised by the immediate transmission of a positive acknowledgment (ACK) by the receiver if the current packet has been successfully received. The second scheme is optional and is known as a four-way handshaking technique. The transmitting station uses a Ready to Send (RTS) notice to inform the receiver and to reserve the channel. The receiver shall then reply by acknowledging with a Clear to Send (CTS). After the reception of the CTS, the transmission shall proceed. As in the basic scheme, the receiver shall also immediately acknowledge the transmitted data packet if successfully received. If the CTS is not received by the source, it is assumed that a collision has occurred and the RTS transmission is rescheduled. With this scheme, collision may only occur on the first RTS frame. The RTS/CTS scheme also enhances the system performance by reducing the duration of collisions when long packets are transmitted [5].

The IEEE 802.11 MAC uses Inter Frame Space (IFS) timing to control the access to the channel. Each station is allowed to transmit only if it has sensed the medium to be idle for at least a Distributed IFS (DIFS). In addition, it shall also wait for a random back-off after DIFS, prior to attempting to transmit. The time duration between the reception of data and the transmission of an acknowledgment is called the Short IFS (SIFS). Figure 1 shows the cycle of the basic access mechanism for a successful transmission. After this cycle, all the stations may contend again for access to the medium.

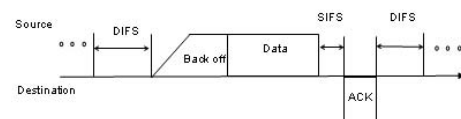


Fig. 1. DCF Basic Access Mechanism

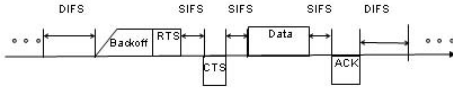


Fig. 2. DCF RTS/CTS Access Mechanism

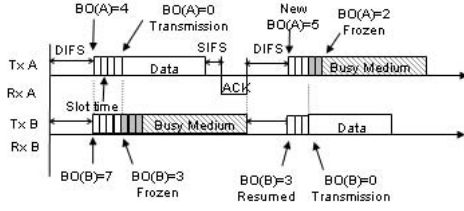


Fig. 3. Contention Window Mechanism

Figure 2 shows the cycle of the RTS/CTS access mechanism for a successful transmission. The contention for the medium is similar. RTS and CTS frames are now introduced at SIFS intervals. Note that IFS timings do not depend on the access scheme but depend only on the PHY (see Table I). However, SIFS is always smaller than DIFS in order to prevent any other station trying to access the medium. Thus, priority is given to the current transmitting station. Collisions are unable to occur as a result of the inability of another station to detect the medium as being idle for a DIFS until the end of the ACK.

The back-off time following the DIFS is slotted and a station is allowed to transmit only at the beginning of each slot. This slot time size is the time needed for any station to detect the transmission of a packet from another station and is PHY dependent [5]. DCF uses an exponential back-off scheme to determine the random back-off timing. The back-off time is determined by:

$$\text{Backoff Time} = \text{Backoff Counter} \times \text{Slot Time} \quad (1)$$

where the back-off counter is uniformly and randomly chosen in the range $[0, W-1]$. W is called the Contention Window. The back-off counter is decremented when the medium is sensed as idle and then frozen if the medium is sensed as busy. The counter is resumed when the medium is sensed as idle again after DIFS. Transmission may proceed when the counter has reached zero. Figure 3 shows an example of the contention window process. After sensing the medium as idle for a DIFS time, Tx A and Tx B randomly set their back-off counter to 4 and 7 respectively. The back-off (BO) counters are decremented until either Tx A or Tx B becomes zero. BO(A) reaches zero when BO(B) is equal to 3, and consequently Tx A starts transmitting data whilst Tx B freezes its counter. Once the transmission cycle is finished, Tx A and Tx B restart sensing the medium. Tx B shall reactivate its BO(B) that was frozen at 3, whereas Tx A uses a new one (BO(A) = 5). The contention window W depends on the number of failed transmissions for the current frame. A transmission is considered as failed when a collision has occurred, i.e. when the back-off counters of two or more stations reach zero at the

TABLE I
MAC TIMING PARAMETERS

	IEEE802.11a	IEEE802.11b
Slot Time (μs)	9	20
SIFS (μs)	16	10
DIFS (μs)	34	50
PIFS (μs)	25	30
CW_{min}	15	31
CW_{max}	1023	1023
ACK (μs)	44 (mode 1)	Mode dependent
Av. Backoff	67.5	310

same time.

W is initially set to CW_{min} for the first transmission attempt. After each failed transmission, W is doubled up to:

$$CW_{max} = 2^m \times (CW_{min} + 1) - 1 \quad (2)$$

where m is called the maximum back-off stage. Once it reaches CW_{max} , it remains at this value until it is reset. W is reset to CW_{min} after each successful transmission. The value of W is then:

$$W = 2^i \times (CW_{min} + 1) - 1 \text{ if } 0 \leq i \leq m \quad (3)$$

$$W = CW_{max} \text{ if } m \leq i \quad (4)$$

where i represents the number of unsuccessful attempts. Similar to IFS timings, the contention window parameters are PHY dependent (see Table I). The Point Coordination IFS (PIFS) is always smaller than DIFS and larger than SIFS:

$$SIFS < PIFS < DIFS \quad (5)$$

The use of PIFS will be explained in the next section. The average back-off defines the back-off duration for 'lightly loaded networks', i.e. when each station has access to the channel after the first back-off attempt. Upon this assumption, the contention window length is therefore CW_{min} . The average back-off duration is then:

$$\text{Average Backoff} = \text{Slot Time} \times \frac{CW_{min}}{2} \quad (6)$$

From figures 1 and 2, we can see that a successful cycle duration with the basic and RTS/CTS schemes are:

$$T_{success}^{basic} = DIFS + Backoff + Data + SIFS + Ack \quad (7)$$

$$T_{success}^{rts} = DIFS + Backoff + RTS + CTS + Data + 3 \times SIFS + Ack \quad (8)$$

If collisions occur, then these two equations are transformed into:

$$T_{collision}^{basic} = DIFS + Backoff + Data \quad (9)$$

$$T_{collision}^{rts} = DIFS + Backoff + RTS \quad (10)$$

In the case of the IEEE 802.11a PHY, ACK, RTS and CTS frames are transmitted with mode 1. The duration of Data is

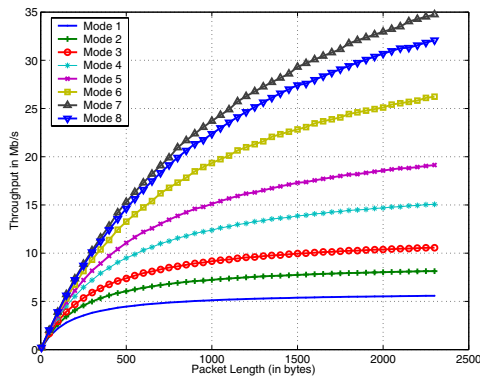


Fig. 4. Throughput - DCF - Basic Access

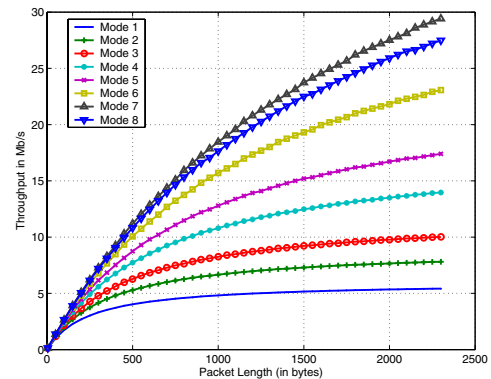


Fig. 5. Throughput - DCF - RTS/CTS Access

mode dependent as well as packet length dependent. The total throughput for both schemes is then given by:

$$\text{Throughput} = \frac{\text{Transmitted Data}}{\text{Transmission Cycle Duration}} \quad (11)$$

Figures 4 and 5 show the throughput of the system under the 'lightly loaded network' conditions for the 8 operating modes of the IEEE 802.11a PHY layer for different packet lengths and for the basic DCF access and the RTS/CTS access scheme respectively. We can see that the throughput is packet length dependent, especially for higher modes. This can be explained by the fact that the MAC overheads are considerably longer compared with the data transmission duration if packets are small. Applications requiring high bit rates are therefore likely to use larger packets. For example, in figure 4, mode 6 with 250 byte long packets offers a throughput of 7Mbps/s whereas 1000 byte packets lead to a throughput of 18Mbps/s. However, longer packets are more likely to be corrupted.

By comparing figures 4 and figure 5, we can see that the basic scheme offers better throughput than the RTS/CTS access technique. The RTS/CTS scheme decreases the efficiency since it transmits two additional frames without payload and two SIFS are introduced. This is only true under the assumption that each station has access to the medium after the first attempt. This is not the case any more when the number of users increases. This case will be detailed in section IV.

III. POINT COORDINATION FUNCTION

The optional PCF has been designed to support time-bounded services and can only be deployed on infrastructure network configurations. It provides a contention free period for transmission by implementing a polling access method. However, it relies on the asynchronous access of the DCF [1]. As stated earlier, DCF and PCF alternate and form a super-frame.

This access method uses a point coordinator (PC) also called an Access Point (AP). The PC polls and coordinates stations and lets them have priority access to the medium. It therefore eliminates contention among stations. The PC gains control of the medium periodically. Once the PC gains control of the medium, it begins a contention free period during which

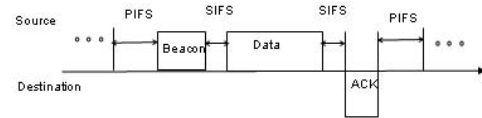


Fig. 6. PCF Access Mechanism

the access to the medium is completely controlled by the PC. During the PCF, a station can only transmit after being polled. PCF starts with a beacon frame. A beacon frame is a management frame that maintains the synchronisation between stations and delivers timing related parameters. Beacon frames are periodically delivered at each Target Beacon Transition Time (TBTT). The TBTT defines the time duration before the next beacon frame [6]. After the initial beacon frame, the PC shall wait for at least one SIFS before transmitting one of the following: a data frame, or a Contention-Free poll (CF-poll) Frame or, a Contention-Free poll and data frame. A CF-poll frame is a request from the PC to poll stations. Upon being polled, stations acknowledge successful reception. Depending on the PCF length, and the data length, several data transmissions (with ACK) can take place in a contention free period after a SIFS interval. Figure 6 shows the basic PCF access with only one data frame transmitted. The priority of PCF over DCF is guaranteed with PIFS being smaller than DIFS. This ensures that other stations will not attempt to access the channel. After the beacon frame, data shall be transmitted after SIFS, and then acknowledged after SIFS. The basic cycle is therefore: PIFS + Beacon + SIFS + Data + SIFS + ACK. The beacon frame duration depends on the content of the body frame (timing, association, authentication parameters) and it has been assumed to be $36\mu s$ [7]. The throughput is derived in the same way as with DCF. Figure 7 shows the throughput performance for different packet lengths and for the operating mode of the IEEE 802.11a PHY. As with DCF, the throughput increases as the packet length increases. By comparing figures 4 and 7, we can see that PCF offers slightly better performance over Basic DCF since there is no need for a back-off (no contention) and since a station has to wait for a smaller time interval (PIFS is smaller than DIFS).

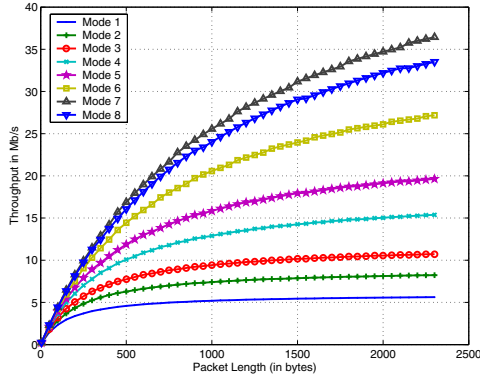


Fig. 7. Throughput PCF - Basic Access

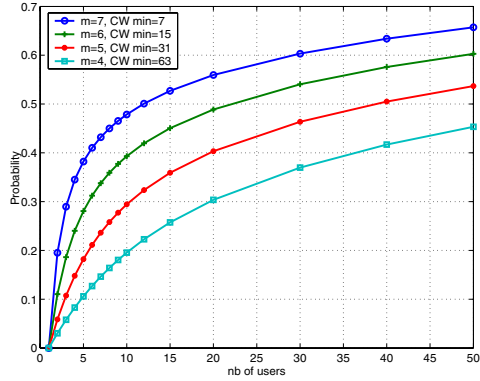


Fig. 8. Probability of Collision

IV. THROUGHPUT AND DELAY ANALYSIS WITH MARKOV CHAINS

In the previous study, it was assumed that stations have access to the medium after the first attempt and there were no collisions. In the case of several users (more than 3), this assumption is no longer valid. The random back-off can not be taken as the average and the probability of collision is not zero anymore. In [5], Bianchi developed a theory based on Markov Chains and stochastic processes to analyse the performance of IEEE 802.11 DCF MAC taking into account the probability of collision with different numbers of users. He assumed that the probability of collision is constant and independent for each transmitted packet, that the channel is ideal without any hidden terminal, and the number of stations is fixed during the simulation. He also assumed that the transmission queue of each station is non-empty (saturation condition). This theory has also been studied in [8] and [9] with an IEEE 802.11b PHY. Here, we will apply it to the IEEE 802.11a PHY. The DCF access scheme is considered. Due to space limitations, the reader is referred to [5], [8] and [9] for the full theory. Figures 8 and 9 show the probability of collision and the probability that a station transmits in a generic slot time for different numbers of users and for different CW_{min} . CW_{max} remains the same for all simulations. From figure 8, we can

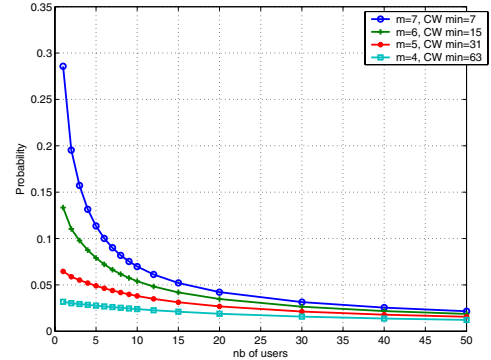


Fig. 9. Probability of Transmission in a generic slot time

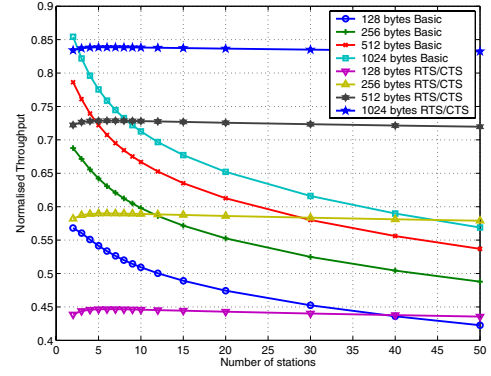


Fig. 10. Normalised Throughput

see that as the number of users increases, the probability of collisions increases as well. As CW_{min} increases, the probability of collision decreases. This is explained by the fact that there are more slot times available as CW_{min} gets larger, so it is less likely for two stations to have their counter equal to zero at the same time. With 10 users, a CW_{min} of 7 leads to a probability of collision of almost 0.5. Using a CW_{min} of 63 reduces the probability of collision to 0.2. From figure 9, we can see that the probability that a station transmits in a generic slot time decreases as the number of users increases. This is explained by the fact that there are more stations contending the channel, so each of them has less chance to transmit. When CW_{min} increases, as there are more slot times before the counter reaches zero, the probability of transmission decreases as well. Note that the IEEE 802.11a PHY parameters for the MAC are $m=6$ and $CW_{min} = 15$. The normalised system throughput, defined as the fraction of time used to successfully transmit payloads bits, is given by:

$$S = \frac{E[\text{Payload Tx in a Slot Time}]}{E[\text{Length of a Slot Time}]} \quad (12)$$

Figure 10 shows the normalised system throughput for the two DCF access schemes for different numbers of users, and different packet lengths, under mode 1 of IEEE 802.11a PHY-layer and ETSI-Channel A. We can see that the basic access throughput decreases rapidly as the number of users increases

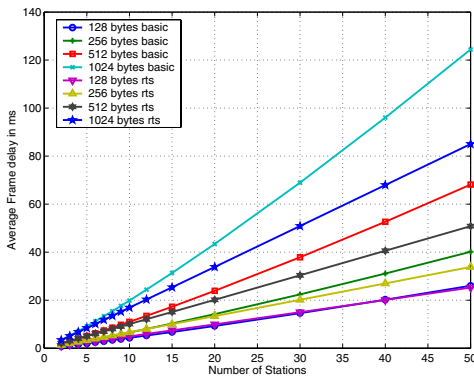


Fig. 11. Average Frame Delay

compared to the RTS/CTS throughput which remains almost constant. This is due to the fact that the probability of collision increases. With the RTS/CTS scheme, only the first RTS frame is lost whereas in the basic scheme the whole data frame is lost. The difference is therefore more important with long packets. For a small number of users, the RTS/CTS scheme uses some of its bandwidth for RTS frames, where the collision probability is low. It therefore does not make good advantage of the channel resources. With 1024 byte long packets and with 10 users, the offered throughput is 11% higher for the RTS/CTS scheme than the basic scheme. On the other hand, with 128 byte long packets, the offered throughput is 5% for the basic scheme. We therefore recommend the use of RTS/CTS for long packets and the use of the basic scheme for small packets. Figure 11 shows the average frame delay under the same PHY and channel conditions. We can see that the RTS/CTS scheme provides better delay performance as the number of users increases, since only the RTS frame is lost in the case of collision, whereas the basic scheme loses the whole data frame.

V. IEEE 802.11E MAC

As explained in the previous sections, the IEEE 802.11 PCF has been designed to support time-bounded services. However, there are problems that constrain its use. One of them is the unpredictable beacon delay due to the unknown transmission time of the polled stations. At TBTT, the PC schedules the beacon as the next frame to be transmitted, but it can only be transmitted if the medium has been sensed as idle for at least PIFS. The medium may not be idle at this time and the beacon frame would be delayed. This would automatically delay the time-bounded data frames that were set to be sent under the CF mode. Another problem is the unknown duration of the data frame transmitted by polled stations. These frames may have variable lengths and can be sent with different transmission modes. This can not be controlled by the PC [6]. In order to support QoS, the IEEE 802.11 Task Group E is currently developing an enhanced version of the IEEE 802.11 MAC called IEEE 802.11e. This enhanced version, defined as the Hybrid Coordination Function (HCF), uses the Enhanced DCF

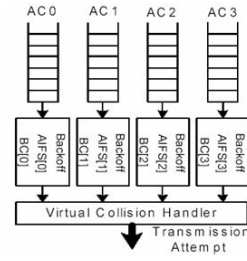


Fig. 12. Four Access Categories for EDCF [10] [11]

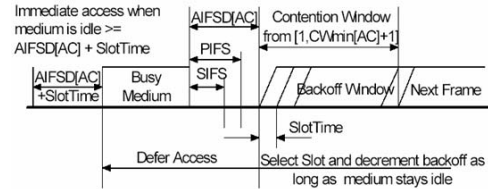


Fig. 13. Multiple back-off with different priorities [6] [12]

(EDCF) for the contention access period. As in the IEEE 802.11 MAC legacy, a contention free period and a contention period shall alternate.

One major enhancement to support QoS is that EDCF has the ability to differentiate data using different priorities with multiple queues whereas DCF only supports one single FIFO regardless of the priority. Each station under EDCF defines 8 user priorities (UP) and each frame from higher layers is mapped onto one of the four access categories (AC) as shown in figure 12. A virtual collision handler is used whenever more than one AC finishes the back-off at the same time within one station. The back off and the contention window required for each packet are parameterised with AC specific parameters. Arbitration Interframe Space (AIFS) is introduced, which is at least as long as DIFS and can be enlarged individually for each AC as shown in figure 13. AIFS are AC dependent and are given by:

$$AIFS(AC) = SIFS + \alpha(AC) \times Slot\ Time \quad (13)$$

where $\alpha(AC)$ is an integer depending on the AC. The smaller the $\alpha(AC)$, the higher the priority. Table 2 shows the AC dependent parameters used for the simulation over IEEE 802.11a PHY and under lightly loaded network. α values are not defined by the standard by an external scheduler, carefully chosen depending on the relative priorities to be assigned. The achievable throughput for the different access categories are shown in figure 14 for mode 3. Because of its large IFS compared to DIFS (for the same contention window), AC 1 leads to worse performance over the legacy DCF scheme. On the other hand, AC 2 and AC 3 offer better throughput performance, even if their AIFS is larger than DIFS (0.8 Mbit/s gain for AC 2 with 500 byte long packets). This is due to their contention windows which are much smaller, so stations need to wait for a smaller back off to access the channel.

TABLE II
EDCF PARAMETERS FOR QoS DIFFERENTIATION

AC	CW_{min}	CW_{max}	α	AIFS μs	Av. Backoff μs
0	15	1023	7	79	67.5
1	15	1023	7	79	67.5
2	7	15	4	52	32.5
3	3	7	2	34	13.5

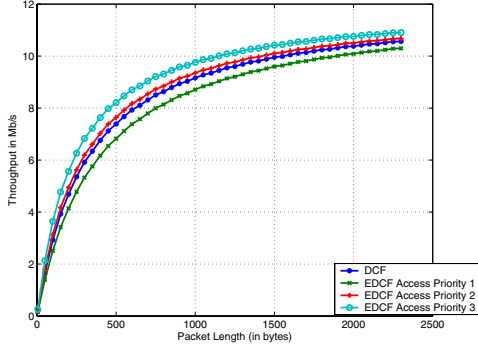


Fig. 14. Throughput for ACs in EDCF

However, EDCF on its own can not provide effective traffic protection and QoS guarantees. This would only be achievable with a polling scheme. The contention free period of HCF is a polling scheme based on the PCF. A contention free burst (CFB) [10] is formed by a sequence of transmission opportunities (TXOP) (see Figure 15). Each station may ask for a transmission opportunity with its starting time and its duration. The Hybrid allocator in the HCF will allocate these resources and then secure the channel against other stations trying to access the PHY. These TXOPs can improve the throughput performances since overhead will be reduced for

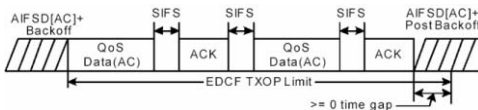


Fig. 15. Transmission Opportunity in EDCF [10]

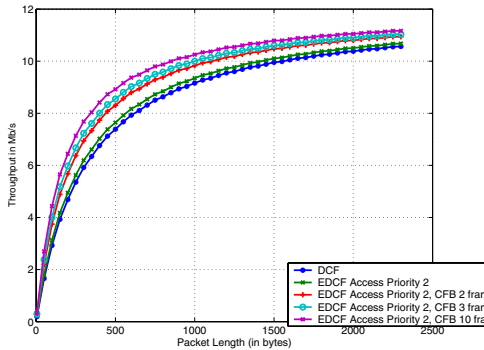


Fig. 16. Throughput with CFB

every transmission (see figure 16 for mode 3). With 500 byte long packets, using 10 frames in CFB offers a 1.5Mbps/s gain over the legacy DCF. Throughput improvements are explained by the fact that a station can transmit multiple frames from the same AC consecutively, with a SIFS and an ACK, without contending for the channel as long as the whole transmission time does not exceed the TXOP limit determined by the AP.

VI. CONCLUSIONS

In this paper, the IEEE 802.11 MAC has been presented. A detailed analysis of the throughput performances for the DCF/PCF access has been carried out, along with the Markov Chains based analysis of the impact of the number of users. Long packets provide better throughput than small packets and are preferable for high bit rate applications. However, for a high number of users, the basic access scheme offers better throughput than the RTS scheme for small packet. For longer packets, the RTS/CTS scheme is preferred (11% gain for 10 users with 1024bytes long packet). The enhanced IEEE 802.11e has been presented with the EDCF performance for service differentiation via ACs. Provided for traffic with different priorities, service differentiation leads to throughput improvements. However, the differentiation can no longer be guaranteed if two stations want to transmit two streams with the same priority. To overcome this problem, the polling scheme of the HCF should be used. The use of TXOP and CFB enhances the throughput performance and is more suitable for time-bounded applications.

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